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ON EARTH CURRENT OBSERVATIONS AT TOTTORI SAND DUNE

By

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Abstract

Simultaneous observations of electric and magnetic fields were made at Tottori Sand Dune and about 100 events were studied in some detail. Strong polarization and large daily variation were found in the electric field. Apparent resistivity was estimated from the ratio of the electric field to the magnetic field and a transfer function was calculated by taking the magnetotelluric method into account. Characteristic features of the field were found in these treatments especially for short period variations.

1. Introduction

When we measure electric potential difference under the name of earth current, it is known that earth current has a preffered direction along which the field tends to polarize, and the direction depends on topographical features. This characteristic, after Yoshimatsu [1957], is classified into the following three types:

i) Near the sea the component perpendicular to the coast line predominates.

ii) In the case of observations at a peninsula, the lateral direction which crosses it most directly prevails.

iii) When there exists a river or mountain region the electric field tends to run parallel to them.

The present observations were made at Tottori Sand Dune which adjoins the Japan Sea. The nearest pole to the coast is only 200 meters away from it and thus the condition exactly corresponds to i). The Japan Sea is rather shallow and therefore it is of interest to see whether this shallow sea affects the direction of the electric field. Another point of interest is what sort of influence or feature is to be seen in earth current observations at such a place

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as a sand dune. In an ideal case, i.e. when the earth is assumed to be semi-infinite with plane surface and with uniform conductivity the electric field, say, E_x, is in the following relation to the magnetic field, H_y, perpendicular to it, as

$$E_x/H_y = 1/\sqrt{0.2\sigma T}, \tag{1}$$

where T and σ are period of variation in seconds and electric conductivity of the earth in mho/meter respectively, and the electric and magnetic fields are measured in mV/km and gamma respectively. This relation is rarely applicable in practical cases, though it may be a measure for estimating the underground conductivity. Cagniard's [1953] method of magnetotellurics is another possible measure, in spite of the limitations pointed out by many authors. In the present study we did not apply his method, one of the reasons being the absence of short period variations in the magnetic data, but we intend to apply his method in future.

As for the application of the earth current for the investigation of the earth's interior, various comments have been presented, most of which may be reasonable. The most impotant problem is whether observed electric fields are really a part of the electro-magnetically induced field and whether it reflects directly the electric state of the earth's interior. Although the present observation was made at a topographically rather complicated place and more or less this is the case anywhere in Japan, enough care would make practical application possible.

2. Instrumentation

Observations were made at Tottori Sand Dune located in the western part of Honshu Island. The sand dune adjoins the Japan Sea. The surrounding

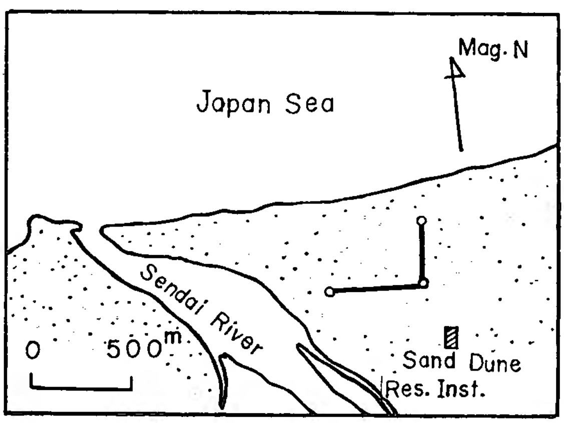

Fig. 1. Location of observing station. Three poles are shown by hollow circles.

topography is shown in Fig. 1 with the position of electric poles. The three poles are north, west and a common one which was used both as south and east pole. North-south and east-west distances are 370 and 500 meters, respectively, and the north pole is only about 200 meters from the coast line which runs nearly in an east-west direction. Each pole is made of four pieces of charcoal stick, about 30 centimeters long and 3 centimeters in diameter. They are buried about 150 centimeters deep in sand, and are packed by powdered charcoal for reducing the contact resistance. Contact resistances were between 1000 Ω and 1100 Ω. Resistance of the earth between the poles is within a few tens of ohms. A signal from each pole is connected directly to the recorder, whose impedance is more than one meg-ohms which is nearly 10^4 times larger than source resistance, thus rendering negligible the variation of the latter. Chart speed was 6 centimeters per hour, and the sensitivity on the chart is 2.0 mV/km/mm for the east-west component and 2.7 mV/km/mm for the north-south.

The magnetic field was observed at the same time very near the site of the common pole using a flux-gate type magnetometer. The three components (H, D, Z) of the field were recorded on a dot-marking-type recorder with the chart speed of 2.5 cm/hour. The low chart speed of the recorder made it difficult to analyse short period variations such as $T<5$ minutes, though it was possible for the electric field. Sensitivity of the three components (H, D, Z) on the chart was 1.38, 1.78 and 0.98 gamma/mm respectively.

3. Results

Observations were initiated on July 21, 1970 and are still continued. About one hundred events were analysed from the data obtained until the end of August 1970, though some components were lacking in these data. The events contain variations with various periods from 8 minutes to diurnal. Figs. 2 and 3 are two examples of the events, the former is a bay type one and the latter is of much shorter period, though the latter is lacking the EW component of the electric field. In these figures, curves are arranged so as to have the same sensitivity each for the electric and magnetic fields. The sense of the field is toward the top of the figure, positively westward and northward for the electric field, and positively increased for the H, westward and downward for the D and Z components of the magnetic field, throughout the present paper. From the sensitivity shown in the figure, the amplitude of variation can be found. It may apparently be seen from these two examples that the variation of the electric field is fairly large, though these are not extreme cases.

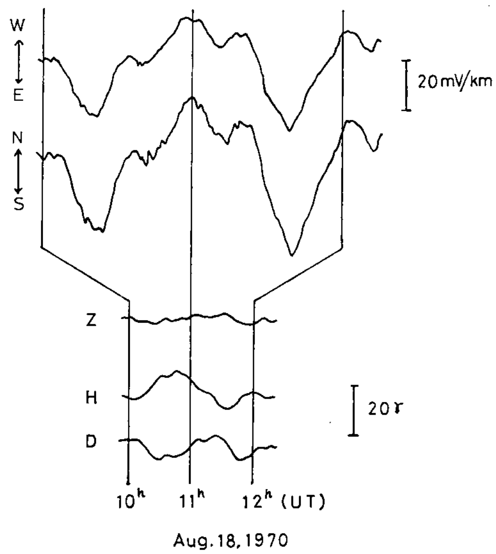

Fig. 2. An example of electric and magnetic field variation. The sense of magnetic field is positively downward, increased and westward to the top of the figure respectively for Z, H and D component.

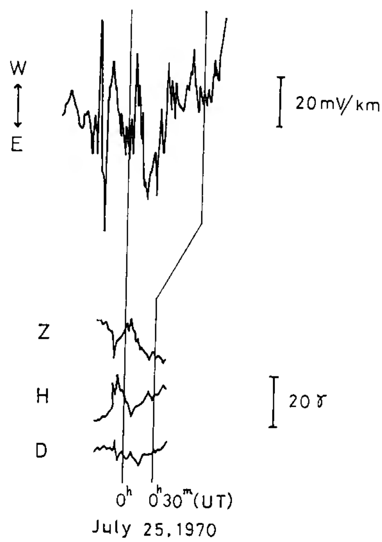

Fig. 3. An example of electric and magnetic field variation. The sense of the field is the same as in Fig. 2.

The solar daily variation of the electric field is also large at Tottori as shown in the next figure.

Fig. 4 shows solar daily variation of the electric and magnetic fields which are averaged over selected three days when both fields are considerably quiet. Calculated values were smoothed out approximately. As the scale in the figure shows, the amplitude of the daily variation of the electric field is about 100 and 40 mV/km for the east-west and the north-south components respectively, and this is very large compared with other stations. As the corresponding geomagnetic field is fairly normal, this seems to suggest the effect of a thin layer near the surface of the earth such as a characteristic conductivity distribution which would be highly resistive with low current density.

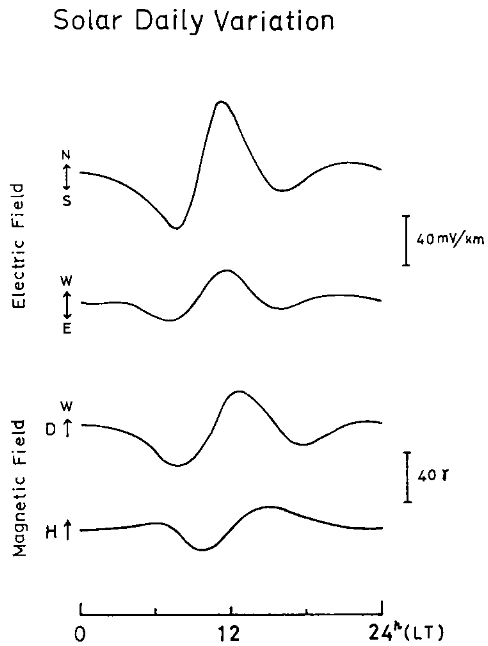

Fig. 4. Solar daily variation of electric and magnetic field which was calculated from three comparatively quiet days.

Conductivity distribution near the surface yields polarization of the electric field, and in the present case the sea and the sand dune exhibit a sharp contrast with regard to electrical conductivity. The conductivity of sea water is very high compared with sand, accordingly the electric potential in the sea becomes equal everywhere comparatively quickly, and the electric field in the sand dune seems to tend to take a direction perpendicular to the coast. If we call here this direction of polarization the *principal direction*, it is nearly northwest-by-west regardless of the period of variation. In Fig. 5, the directions of nearly one hundred events are shown by dots, where the values of ordinate and abscissa of every dot correspond to the amplitude of variation for that direction. In Fig. 6 the principal direction is shown by an arrow on

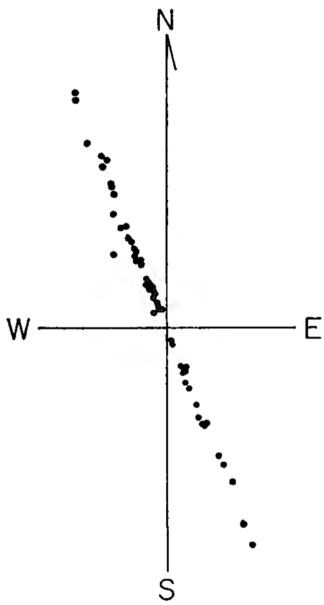

Fig. 5. The direction of 100 variations of electric field. Coordinates of every dot are components of amplitude of variation in that direction.

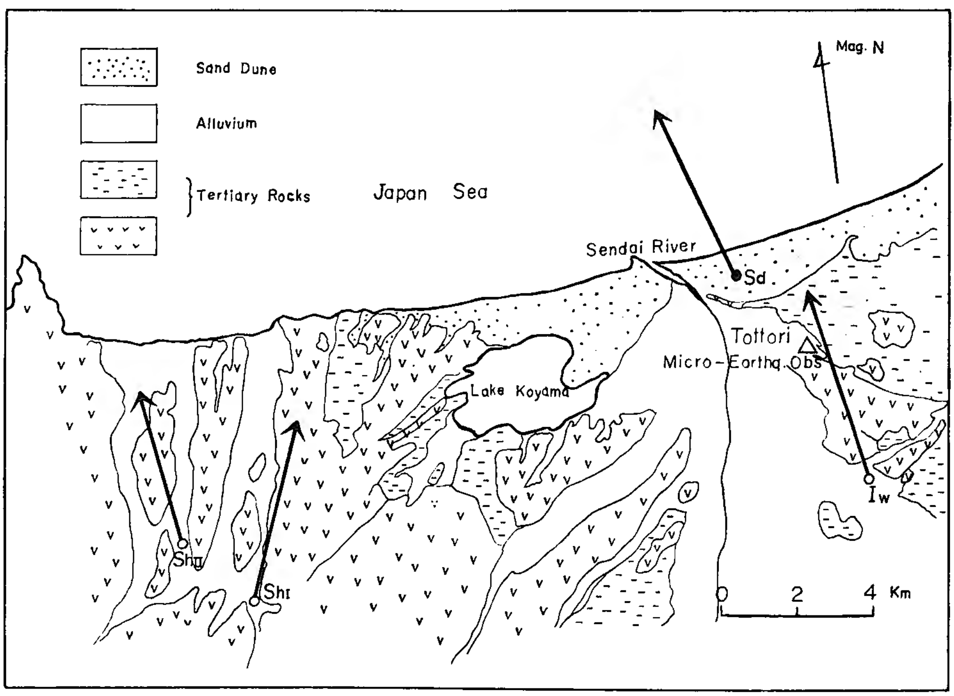

Fig. 6. Principal direction and geological map around Tottori. Sd: Tottori Sand Dune. Iw: Iwakura. Sh-I and Sh-II: Shikano. Arrows indicate principal directions there, but their length has no meaning.

a geological map around the observing station together with those obtained by other researchers. These directions closely resemble each other, all pointing to the sea. For our present case hodographs of a few representative events show more clearly their polarized character as shown in Fig. 7, where the solid line shows variation of the electric field in every five minutes and the dotted line the magnetic field at nearly equal intervals. For the shortest period case in the figure the corresponding magnetic field was hard to read.

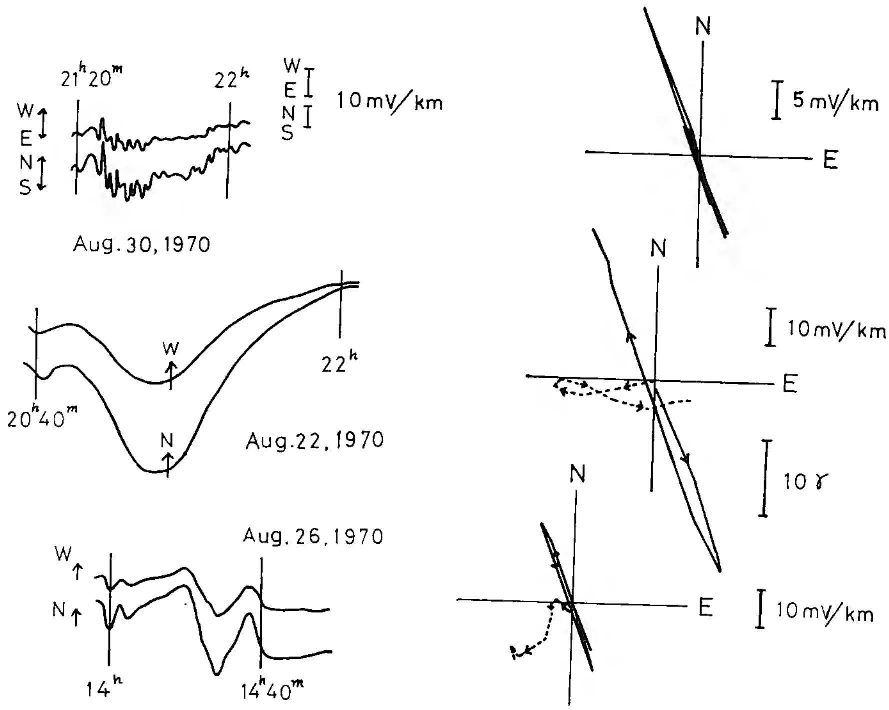

Fig. 7. Examples of electric field of various period, and their hodographs. Note that sensitivity in this case is unequal in two components. In the lower two variations a hodograph of the magnetic field (dotted line) is also shown with electric field (solid line), but for the top the variation is too quick to be caught by fluxgate magnetometer.

For a uniform semi-infinite earth with a plane surface the electric and magnetic fields have a relation as shown in Eq. (1). Such an assumption for the earth is hardly applied in the present case because of the sharp conductivity jump at the boundary of the sea and the sand. These aspects exist only near the surface of the ground, and except in the thin surface layer, the assumption might be applicable; however, we will never be free from the influence of conductivity distribution at the surface so long as observation is made there. Putting aside this problem, however, we calculated the ratio of the electric to the magnetic field for components perpendicular to each other, that is *EW/H* and *NS/D*, where *EW* and *NS* mean electric fields in the east-west and north-south components, respectively. The ratio versus period is plotted in Fig. 8, where the curves indicate the values (E_x/H_y) at various periods when

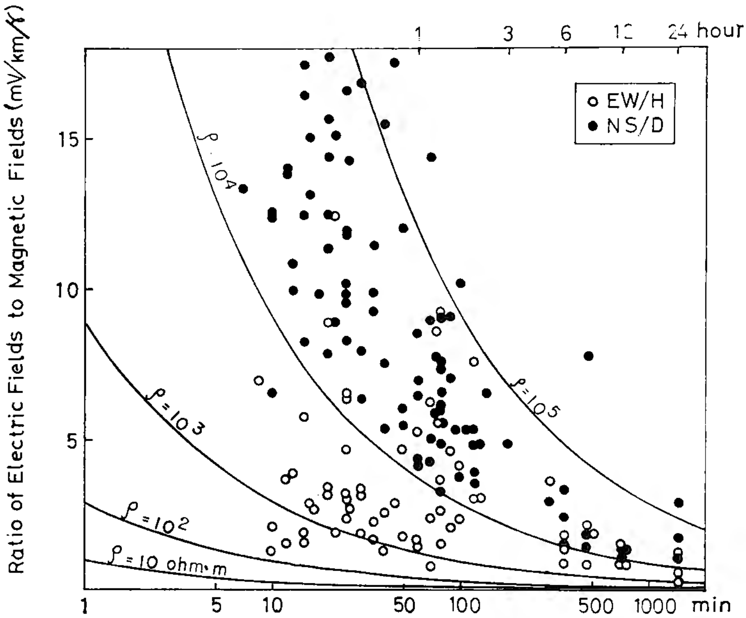

Fig. 8. Ratio of electric field to magnetic field versus period plotting. Hollow circles and full circles correspond to *EW/H* and *NS/D*. Curves of solid line are ideal curves for uniform semi-infinite earth with various resistivity calculated from Eq. (1).

the apparent resistivity, $\rho=1/\sigma$, in Eq. (1) takes various values. It is clearly seen that hollow circles (*EW/H*) and full circles (*NS/D*) make separate groups, and further, two groups are mixed together as the period becomes longer. From another point of view full circles are fairly well sandwiched between two curves $\rho=10^4$ and $\rho=10^5$ ohm-m, whereas hollow circles lie well along a $\rho=10^3$ curve. Interpretation of these features is very difficult, but polarization of the electric field seems to cause the separation of two groups, especially in shorter periods. Meanwhile as the period becomes longer, the deeper part of the earth contributes to both the electric and the magnetic fields, which yields a mixing of the two groups.

Concerning the variation of apparent resistivity across two materials, say *A* and *B*, with different electrical characteristics, Swift [1967] suggested that its tangential component is continuous at the boundary, but its radial component is not. If the tangential and radial components of apparent resistivity of material A are expressed as $\rho_{A/\!/}$ and $\rho_{A\perp}$, respectively, the relation A to B at the boundary is $\rho_{A/\!/}=\rho_{B/\!/}$ and $\rho_{A\perp}\neq\rho_{B\perp}$. On the other hand as to the ratio E_x/H_y, it would be more representative of the apparent resistivity in the direction of electric field, i.e. ρ_x, and therefore in the present case, hollow circles represent the apparent resistivity of the direction tangential to the coast line. In this sense low values of hollow circles and high values of full circles are reasonable, for the former should continue at the boundary to the value of the resistivity of sea water and the latter should not. However this is not appreciable quantitatively, because the resistivity of sea water, which is something about the order of 10^{-1} ohm-m, is much lower than the values given by the hollow circles.

As the polarization of the electric field is strong as already mentioned, the ratio E_x/H_y may rather be discussed in the form of absolute values, i.e. $\sqrt{EW^2+NS^2}/\sqrt{H^2+D^2}$ and this versus period plotting is given in Fig. 9. In this case the circles fairly converge than in the previous result, but essentially the two do not differ much. We cannot at once conclude this value of ρ to be true.

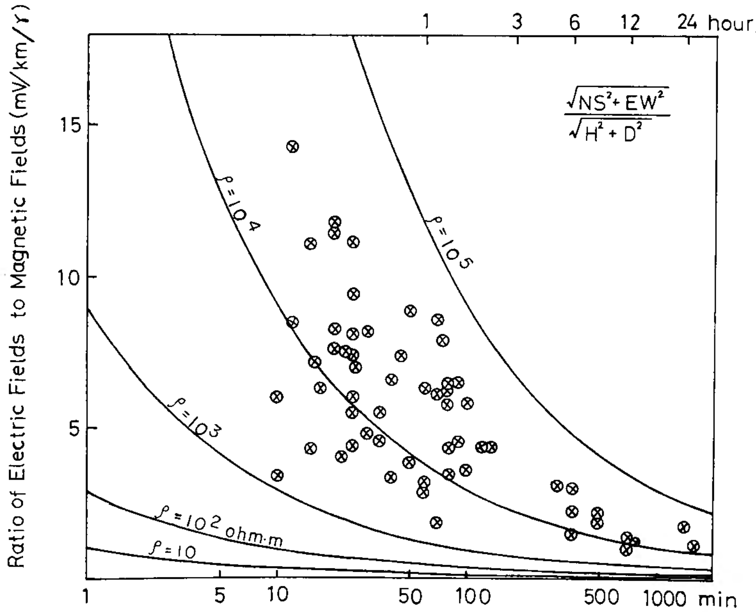

Fig. 9. Ratio of absolute electric field to absolute magnetic field, that is $\sqrt{NS^2+EW^2}/\sqrt{H^2+D^2}$ versus period plotting. Curves of solid line is the same as Fig. 8.

A transfer function may be useful to discuss the distortion of the electric field. We write it as

$$[T]\equiv\begin{bmatrix} T_{EWD} & T_{EWH} \\ T_{NSD} & T_{NSH} \end{bmatrix}, \tag{2}$$

then the electric and magnetic fields are expressed as follows:

$$\begin{bmatrix} EW \\ NS \end{bmatrix}=\begin{bmatrix} T_{EWD} & T_{EWH} \\ T_{NSD} & T_{NSH} \end{bmatrix}\begin{bmatrix} D \\ H \end{bmatrix}, \tag{3}$$

where $[T]$ is a function of period and conductivity. If this relation is applied to the uniform semi-infinite earth model, T_{EWD} and T_{NSH} are equal to zero, and T_{EWH} is equal to T_{NSD}. To calculate $[T]$, the field should be analysed into spectra. However, a simple and approximate method is used. The method is described in the following. From Eq. (3) we have

$$\begin{aligned} EW&=T_{EWD}D+T_{EWH}H \\ NS&=T_{NSD}D+T_{NSH}H, \end{aligned} \tag{4}$$

and from these

$$\begin{aligned} \frac{EW}{H}&=T_{EWD}\frac{D}{H}+T_{EWH} \\ \frac{NS}{H}&=T_{NSD}\frac{D}{H}+T_{NSH}. \end{aligned} \tag{4'}$$

First, all events were classified into groups of the same period, and then EW/H, HS/H and D/H were decided for each event in a group. For example, if there are five events in the group having a period of 20 minutes, five values of EW/H, NS/H and D/H respectively are calculated and they are plotted on EW/H (or NS/H) versus D/H coordinates as Fig. 10, and if five plots are combined into a straight line by the least squares method, T_{EWD} and T_{EWH} (or T_{NSD} and T_{NSH}) are obtained from the gradient and a point of contact for ordinate. In practice, however, instead of (4′) we also used equations obtained from dividing the both sides of Eq. (4) by D instead of H. Theoretically the former and the latter equations should give the same $[T]$, but did not in practice, and to minimize errors values of $[T]$ were decided from equations in which the plotted points are well distributed along the abscissa. Graphs used to decide $[T]$ at every period are shown in Fig. 10, where which equation is used is shown by a line under the value of period T at the top of each graph, and when the graph has underlining under the value of period T the former equation is used. In the figure hollow circles and straight lines combining them are used to decide T_{EWD} and T_{EWH}, and full circles and straight lines T_{NSD} and T_{NSH}. Fig. 11 shows the transfer functions thus decided.

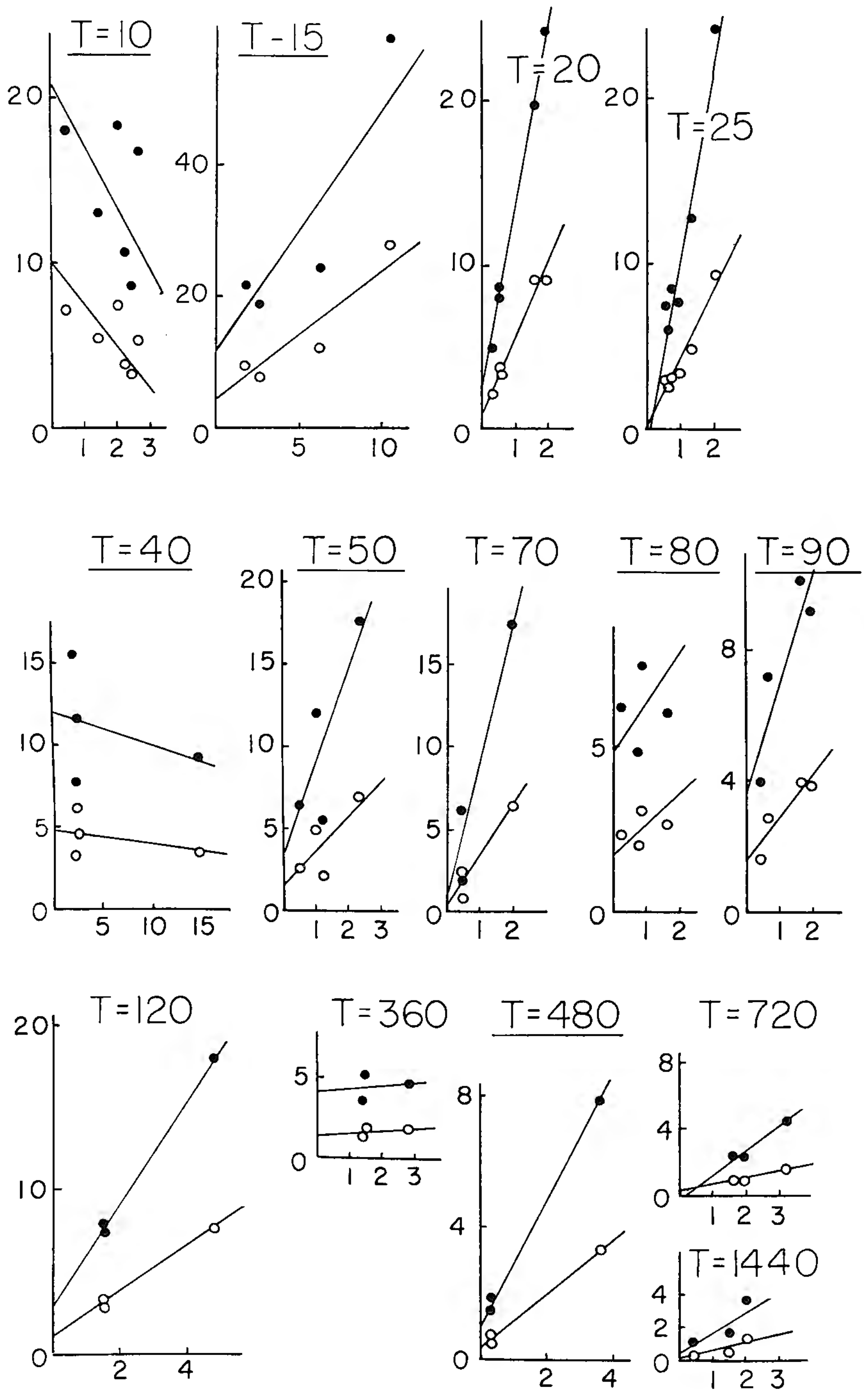

Fig. 10. EW/D versus H/D (or EW/H versus D/H).
NS/D versus H/D (or NS/H versus D/H).
Period T is in unit of minutes. For graphs with underline T-value, the set of coordinate and abscissa adopted is the one shown in parentheses. Note the scale of coordinates.

From the figure the following may be seen. Polarization is appreciable. As to the magnitude of the function, T_{NSD} is the largest and T_{EWD} is the second. As T_{EWD} is not small and T_{NSD} does not resemble T_{EWH}, the present results are far from those of a uniform earth model. These features, however, decay as the period becomes longer. As to the shape of curves, T_{EWD} resembles T_{NSD}, and on the other hand T_{EWD} resembles T_{NSH}. T_{EWD} and T_{EWH} are coefficients which relates to the electric *EW* component with the magnetic *D* and *H* components as the first equation of Eqs. (4). So, in a sense, T_{EWD} and T_{EWH} in a set may correspond to the hollow circles in Fig. 8, and T_{EWD} is more representative of their nature. The same may be said for T_{NSD} and T_{NSH}, accordingly T_{NSD} is representative.

This transfer function is equivalent to apparent resistivity in a sense, thus T_{NSD}, for example, is the apparent resistivity which relates to the electric *NS* component with magnetic *D*. The large value of T_{NSD} comes from the large value of *NS* (and/or small value of *D*), which means little contribution of electric *NS* component to the magnetic *D* field, i.e. a large resistivity between the relation of two fields. The same can be said about the large value of T_{EWD} and the small values of T_{EWH} and T_{NSH}. It may be said on the whole that the apparent resistivity which relates to the *D* field is large, but that which relates to the *H* field is small. These are the very features of the polarization, but they also decay as the period becomes longer.

4. Discussion

Strong polarization of the electric field is caused by the distribution of the sand dune and the sea, and though the Japan Sea is shallow it seems that it has a great influence on the electric field. This polarization yields a difference between *NS/D* and *EW/H*, which in turn cause a characteristic in transfer function especially at shorter periods. These features, however, decay as the period becomes longer, that is to say the contributions of the deeply induced currents on the surface field become clearer.

Although we have not simultaneous records at other stations, the range of daily variation of the electric field is apparently large compared with that at other stations, and this would be the same for shorter periods. As for the magnetic field, Miyakoshi [1969] studied the *Z* component at Tottori and suggested the reverse of sense of its variation in shorter periods such as bay contrary to many other stations in Japan. For other components, however, no unusual feature is found. Further, the normal magnetic field and the abnormally large electric field seem to yield large apparent resistivity as seen in Figs. 8 and 9, and characteristic transfer functions as in Fig. 11.

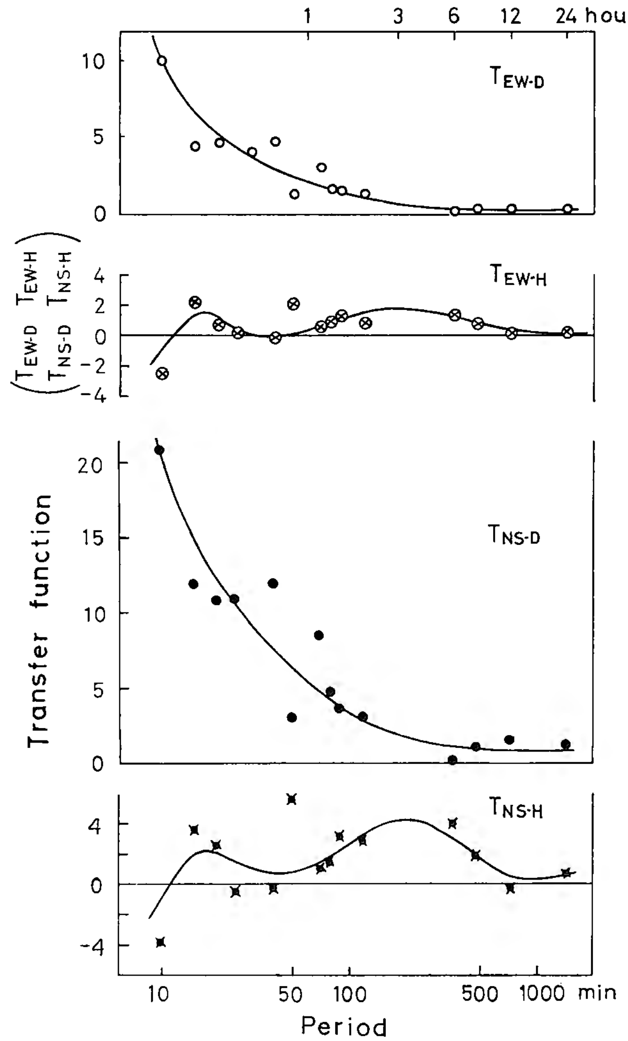

Fig. 11. Transfer functions. Plots are calculated values and solid lines are functions obtained.

The cause of distortion of the apparent resistivity is the distribution of the sea and the sand, and resistance of the sand itself may not be distorted so much. However the value of ρ of the sand on the whole seems to be very large, though the exact value was not decided in the present observation. As the electric field, $\boldsymbol{E}$, and the current density, $\boldsymbol{I}$, have a relation $\boldsymbol{E}=\rho\boldsymbol{I}$, the large value of $\boldsymbol{E}$ does not at once imply the large $\boldsymbol{I}$. In other words the possibility exists that current is small in spite of the large $\boldsymbol{E}$, because of large ρ. Argument is complicated because of anisotropy of the apparent resistivity, but the exact conductivity distribution in the ground should be sought in the future, taking account of the surrounding geological features. We are planning to make the observations of the shorter period magnetic field in the near future.

Acknowledgement

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